Prospects of Open-Charm Asymmetry Measurements at the SPD

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Spin Physics Detector (SPD) at NICA

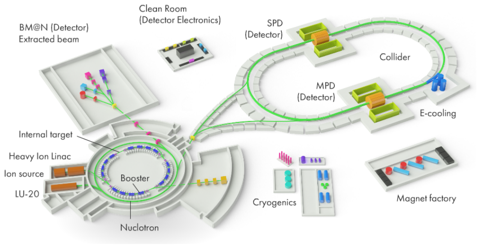


Figure 1: NICA - Nuclotron-based Ion Collider fAcility

- Polarized collisions
  1. $p^{\uparrow}p^{\uparrow}$ at $\sqrt{s} = 27$ GeV
  2. $d^{\uparrow}d^{\uparrow}$ at $\sqrt{s} = 13.5$ GeV
- with polarization $|P| \sim 70\%$

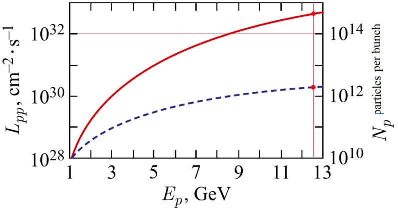


Figure 2: Luminosity and bunch intensity

Prime focus at SPD : to probe unpolarized and polarized gluon parton distribution functions (PDFs) inside nucleons

Transverse Single Spin Asymmetries (SSA)

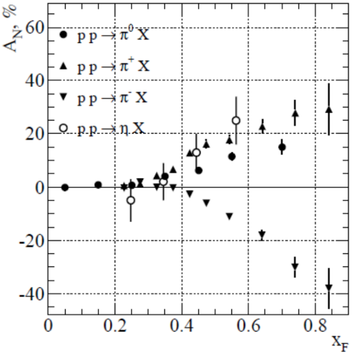


Figure 3: Charged and neutral ion SSA at E704 (Phy.Lett. B (264) 1991, 462-466)

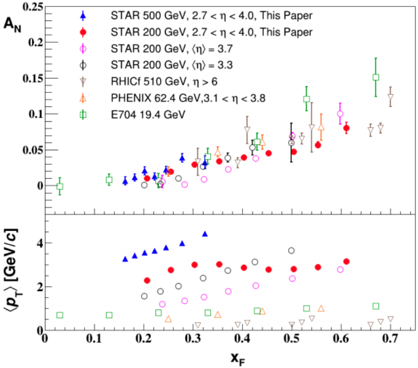
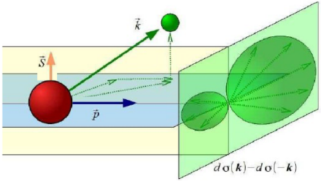


Figure 4: Neutral pion SSA at RHIC experiments

TMD functions like Sivers PDF, Collins FF are used to explain (suprising) large SSA

Gluon TMD : Sivers Function



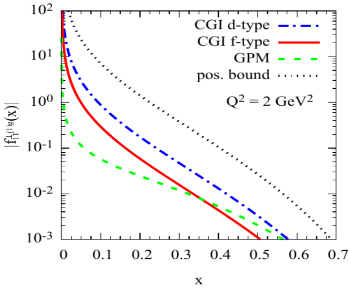
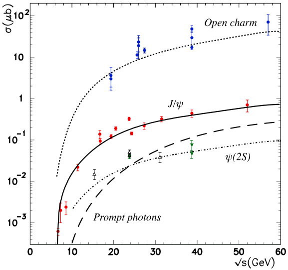
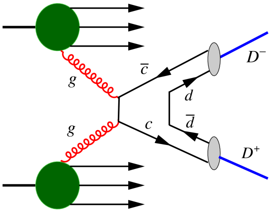


Figure 5: First k_T moment of gluon Sivers for GPM and CGI-GPM (PRD99, 036013 (2019))

- Sivers function ($f_{1T}^{\perp}(x, k_T)$) is the correlation between parton intrinsic k_T and nucleon (transverse) spin
- Transverse single spin asymmetries (A_N) are sensitive to the Gluon Sivers function
- Can be parametrized in generalized parton model(GPM), color gauge invariant GPM(CGI-GPM) descriptions of partonic structure
- Unlike gluon helicity PDF, there has not been extraction of Gluon Sivers function from global analysis
- SPD can provide much needed data points sensitive to Gluon Sivers

SPD : Measurements





- At peak SPD energy gluon fusion process dominates ($\sim$ 70% contribution) charmed meson production, making asymmetries sensitive to the gluon spin distributions
- It is also the highest statistic channel among the three main probes at the SPD
- Among different possible decay modes of charmed mesons, SPD detectors can best measure in hadronic decay channels
  1. $D^0 \rightarrow \pi^+ + K^-$, Branching Ratio 3.89%
  2. $D^+ \rightarrow \pi^+ + \pi^+ + K^-$, Branching Ratio 9.22%
  3. ... and corresponding antiparticles

SPD Stage II : Detector

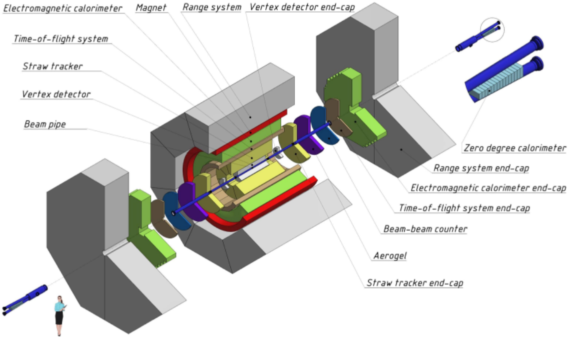
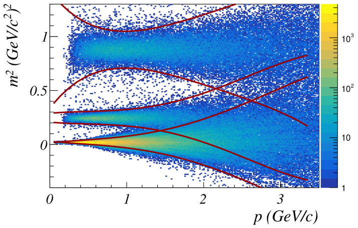


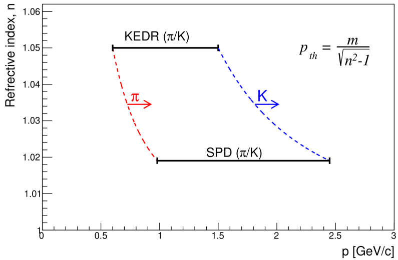
Figure 6: SPD detector in stage II

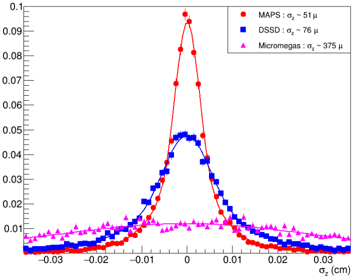
- Vertex detector for short lived particle decays
- TOF+AGel for particle identification
- Straw Tracker for momentum determination

- Event rate at peak luminosity and energy $\sim$ 3 MHz
- Silicon vertex detector : MAPS/DSSD for D-meson decay reconstruction
- Momentum resolution from Tracker : $\frac{\delta_{p_T}}{p_T} \sim 2\%$ for 1 GeV/c tracks with magnetic field $\sim$ 1 T
- Time of flight (TOF) for PID ($\delta_t \sim$ 50 ps), providing π/K separation

Detector Perfomance







- TOF performance:provides a 3σ separation of π/K upto 1.5 GeV/c
- Aerogel can extend it up to 2.5 GeV/c
- Resolution of reconstructed D^0 vertex : $\delta_z \sim 50\ \mu$m for MAPS (D^0 decay length $\sim 120\ \mu$m and $D^{\pm}$ decay length $\sim 310\ \mu$m)

Monte-Carlo Simulations

- Pythia8 + SpdRoot (Geant4 detector simulation + ROOT based reconstruction)
- Subsystems used : beam-pipe, magnet, vertex detector, straw tracker
- Magnetic field : $B_z = 1$ Tesla
- Vertex tracker : 4 layer MAPS (barrel + end caps)
- Event vertex at nominal center
- Ideal particle identification
- PYTHIA minimum bias (except elastic) for background study and open-charm channels for signal (D-meson) study
- D-meson hadronic decay channels forced to enhance statistics in the simulation study

Analysis Details

- Best quality tracks are selected requiring at least 3 (out of 4 layers) Vertex Detector hits
- D-meson decay vertex reconstruction performed with Kalman Filter based KFParticle package
- Reconstruct performed for all possible combinations of (π,K) in the minimum bias event to study combinatorial background
- Mass window cut (1.7 - 2.0 GeV/c^2) applied for all cases for both signal and random background (D-meson mass $\sim$ 1.86 GeV/c^2)
- 4 M open-charm events generated
- 40 M minimum bias (except elastic) events generated

Neutral D Meson : Invariant Mass Starting Point

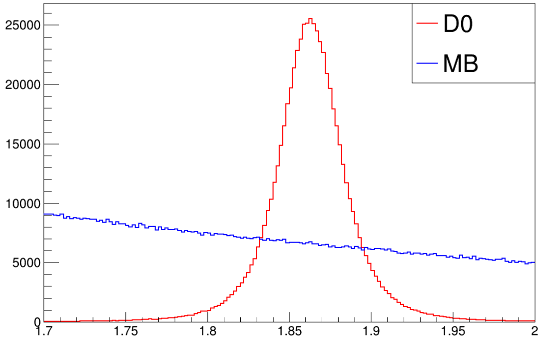


Figure 7: $\pi^+ K^-$ invariant mass (GeV$/c^2$) for both the D^0 signal and combinatorial background from MinBias

Generated : 4 M open-charm events, 40 M MinBias events
Reconstructed : 633533 D^0, 1.02634×10^6 MinBias

Neutral D Meson : Decay Length and Uncertainty

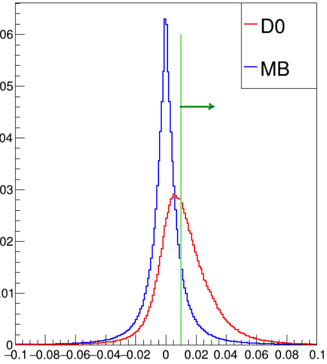


Figure 8: Reconstructed decay length of the π/K pair for signal and background

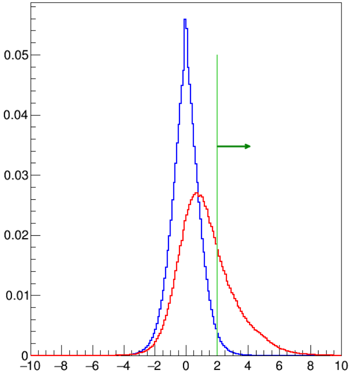


Figure 9: Relative uncertainty of the reconstructed decay length

D Meson Reconstruction Variables

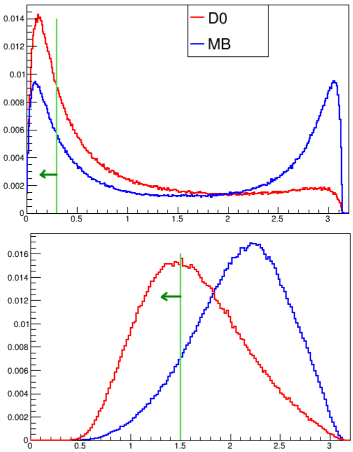


Figure 10: Collinearity angle of mother track (above) and opening angle between daughter tracks (below)

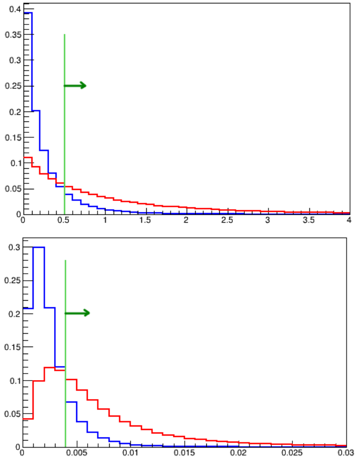


Figure 11: χ^2 (above) and distance (DCA in cm) (below) of mother track from primary vertex

Daughter Track Reconstruction Variables

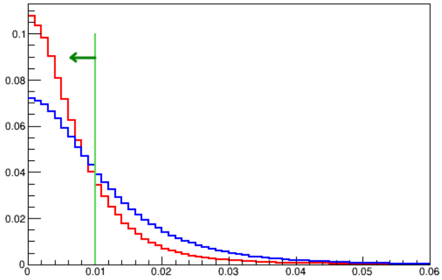


Figure 12: Distance (DCA) between daughter (π and K) tracks in cm

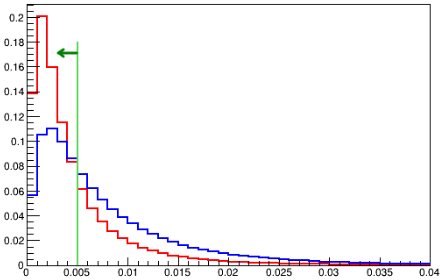


Figure 13: Distance (DCA) between primary vertex and daughter (π, K) tracks in cm

Selection Criteria Suppressing Random Combinatorial Background

- Decay length : $L > 0.008$ cm, $L/\delta L > 2$.
- Collinearity angle : $\theta_{col} < 0.3$ rad
- V0 properties : $\chi^2_{V0-PV} > 0.5$, $DCA_{V0-PV} > 0.004$ cm
- Daughter track properties :
- $DCA_{\pi-K} < 0.01$ cm, opening angle $\theta_{OA} < 1.5$ rad
- Daughter to PV : $\chi^2_{d-PV} > 1.5$, $DCA_{d-PV} > 0.01$ cm
- Daughter to V0 : $DCA_{d-V0} < 0.005$ cm
- Invariant mass window 1.7-2.0 GeV$/c^2$
- $|x_F| > 0.2$ for asymmetry measurements

Invariant Mass After Background Suppressing Cuts

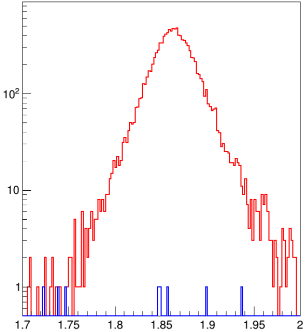


Figure 14: Invariant mass (GeV/c^2) distributions after background suppressing cuts

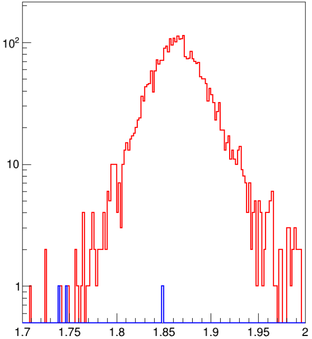


Figure 15: Invariant mass (GeV/c^2) distributions after background suppressing cuts for $|x_F| \geq 0.2$

Started with : 633533 D^0, 1.02634×10^6 MinBias

Before x_F cut : 11456 D^0, 8 MinBias, After x_F cut : 3279 D^0, 3 MinBias

Effect of the Combinatorial Background Suppression

- Signal/Background ratio (S/B) = 1093 (from *generated* MC event ratio $N_S/N_B = 1/10$)
- Assuming 32.8 mb for MinBias and 9.4 μb for open-charm, *produced* event ratio in real data $N_S/N_B = \sigma_S/\sigma_B = 1/3489$
- Correct for proper event ratio
- Correct for proper D^0 branching ratio
- After corrections, expected from data, S/B $\sim$ 1/8 for the ideal scenario (perfect PID, event vertex at the nominal center)

D^0 Background Suppression : Projected One Year Data

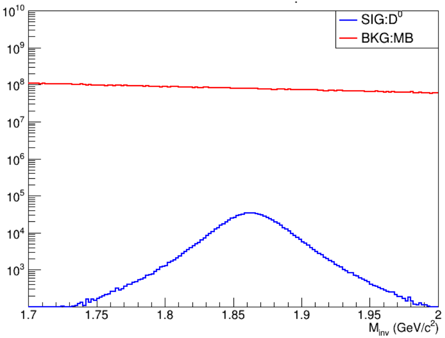


Figure 16: Projected invariant mass (GeV/c^2) of $\pi^+ K^-$ shows orders of magnitude higher background in one year of recorded data in $|x_F| \geq 0.2$

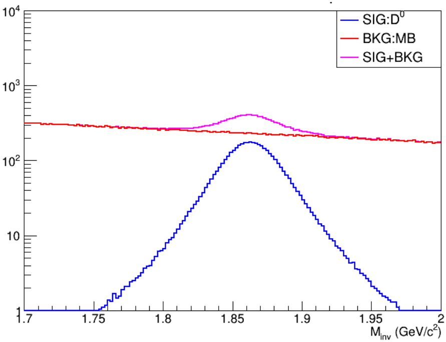


Figure 17: Projected invariant mass (GeV/c^2) $\pi^+ K^-$ after background suppressing selection criteria

Integrated luminosity for $p + p$ at $\sqrt{s} = 27$ GeV, $\mathcal{L}_{int} = 1\ \mathrm{nb}^{-1}$)

D^+ Background Suppression : Projected One Year Data

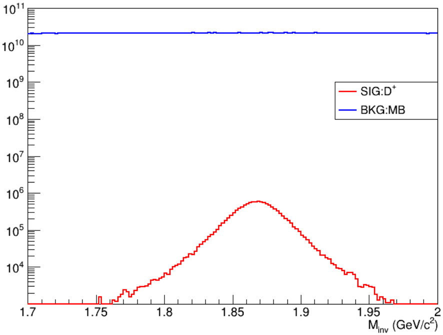


Figure 18: Projected invariant mass (GeV/c^2) of $\pi^+\pi^+K^-$ shows orders of magnitude higher background in one year of recorded data in $|x_F| \geq 0.2$

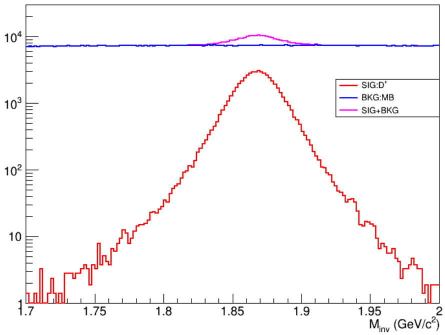


Figure 19: Projected invariant mass (GeV/c^2) of $\pi^+\pi^+K^-$ after background suppressing selection criteria

Integrated luminosity for $p + p$ at $\sqrt{s} = 27$ GeV, $\mathcal{L}_{int} = 1\ \mathrm{nb}^{-1}$)

For Future : Background From Open-Charm Events

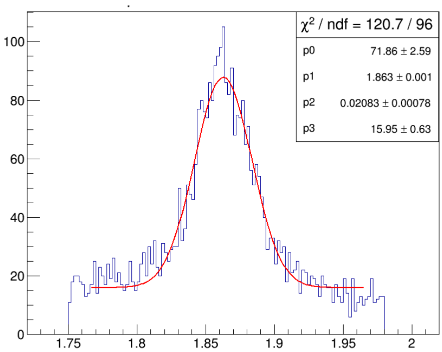


Figure 20: All possible π^+/K^- combinations from open-charm events with D^0 produced

- Even in the open-charm/signal events, there can be multiple π, K combinations
- These combinations also can add to the background
- Plot (left) shows it is a small contribution, especially compared to orders of magnitude higher background form MinBias events
- We neglect this for now

Estimated Statistical Uncertainty of Asymmetry

$$\sigma_{A_N^S} = \frac{\sqrt{\sigma^2_{A_N^T} + r^2\sigma^2_{A_N^B}}}{1-r}$$

- S is signal, B is background, T is total = signal+background and ratio $r = \frac{B}{B+S}$
- $\sigma_{A_N^T}$ and $\sigma_{A_N^B}$ are Poisson uncertainties of total and background counts in the x_F bins in this case
- 4M of open-charm events ($\sim$ 2M events with D^0 forced decay) produces counts :
  1. xF: 0.2-0.3 : 2416
  2. xF: 0.3-0.5 : 841
  3. xF: 0.5-1.0 : 22

SPD NICA

Estimated Inclusive D Meson SSA

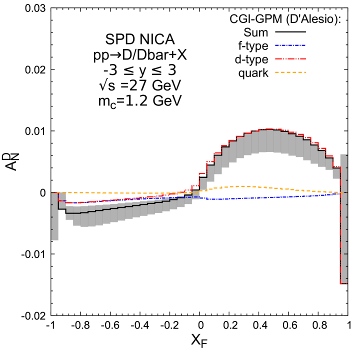


Figure 21: Inclusive D meson transverrse single spin asymmetry with D'Alesio parameters of CGI-GPM model of Gluon Sivers

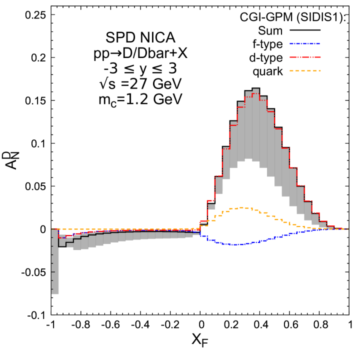


Figure 22: Inclusive D meson transverrse single spin asymmetry with SIDIS1 parameters of CGI-GPM model of Gluon Sivers

V. Saleev, A. Karpishkov (Phys.Part.Nucl.Lett. 20(2023) 3, 360-363). Notice the vertical scale difefrence.

Projected Asymmetry of $A_N^{D^0}$

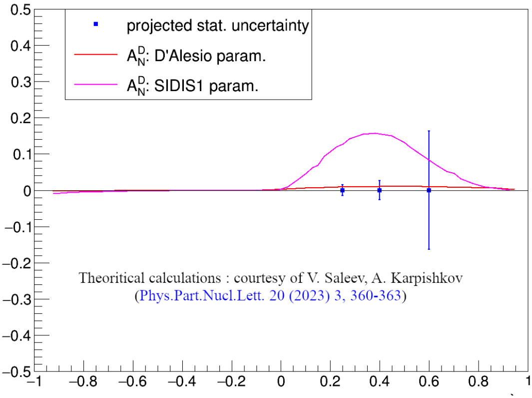


Figure 23: Projected statistical uncertainty of D^0 SSA measurements as function of Feynman-x (x_F). Theoretical lines show inclusive D meson SSA (A_N^D) for different parameterized models of Gluon Sivers function

- Estimated statistical uncertainty of D^0 single transverse spin asymmetry ($\sigma^{stat}_{A_N^{D^0}}$) in the xF bins :
  1. xF: 0.2-0.3 : 0.0156
  2. xF: 0.3-0.5 : 0.0165
  3. xF: 0.5-1.0 : 0.1640

Advances in Understanding Quark Sivers Function (QFS)

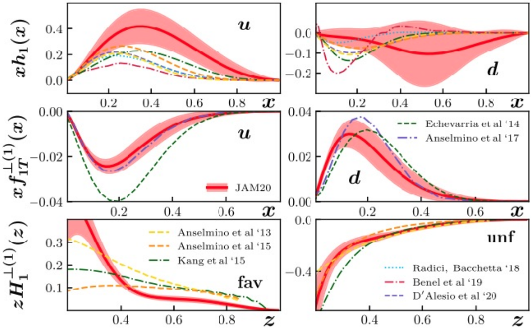


Figure 24: QFS from global analysis (Phys.Rev. D 102 054002(2020))

Require experimental data sensitive to GFS from different systematics i.e. collider, SIDIS

Summary

- D meson analysis technique at the SPD is on the right track
- Statistical uncertainties with (assumed) perfect particle identification shows SPD measurements will be able to reduce model dependence of the Gluon Sivers function
- Both neutral and positive D-mesons show similar (1/8) signal-to-background ratio after suppression of combinatorial backgrounds
- With more aggressive tune of event and track selection criteria, it is possible to improve S/B further
- PID capability is a crucial part of the secondary vertex reconstruction, improving identification in forward directions (end caps) are important
- Large scale simulation data ($\sim$ billions of generated events) are required to properly see effect of cuts on the combinatorial background

Thank You For Your Attention